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Differential EMG Biofeedback for Children with ADHD: A Control Method for Neurofeedback Training with a Case Illustration

S. Maurizio · M. D. Liechti · D. Brandeis · L. Jäncke · R. Drechsler

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Abstract The objective of the present paper was to develop a differential electromyographic biofeedback (EMG-BF) training for children with attention-deficit/hyperactivity disorder (ADHD) matching multiple neurofeedback training protocols in order to serve as a valid control training. This differential EMG-BF training method feeds back activity from arm muscles involved in fine motor skills such as writing and grip force control. Tonic EMG-BF training (activation and deactivation blocks, involving bimanual motor tasks) matches the training of EEG frequency bands, while phasic EMG-BF training (short activation and deactivation trials) was developed as an equivalent to the training of slow cortical potentials. A case description of a child who learned to improve motor regulation in most task conditions and showed a clinically relevant reduction of behavioral ADHD symptoms illustrates the training course and outcome. Differential EMG-BF training is feasible and provides well-matched control conditions for neurofeedback training in ADHD research. Future studies should investigate its value as a specific intervention for children diagnosed with ADHD and comorbid sensorimotor problems.

Keywords Biofeedback training · Electromyography · Neurofeedback control condition · ADHD

Introduction

ADHD is one of the most frequent disorders in child psychiatry, defined by the co-occurrence of symptoms of hyperactivity, impulsivity and inattention (DSM-IV-TR, APA 2000). Researchers have utilized different types of biofeedback (BF) for active treatment, or for control purposes in controlled attention deficit hyperactivity disorder (ADHD) intervention studies. Many studies have shown that neurofeedback (NF) training based on self-regulation of neural EEG (electroencephalogram) activity is an effective treatment for children with ADHD in comparison to other interventions and control conditions (see meta-analysis by Arns et al. 2009; for reviews see e.g. Drechsler 2011; Fox et al. 2005; Heinrich et al. 2007). The two common NF training protocols require tonic regulation of frequency bands, typically over minutes, or phasic regulation of slow cortical potentials (SCPs), typically over seconds. Sophisticated recent NF training studies (Gevensleben et al. 2009; Liechti et al. 2012; Wangler et al. 2011) combine both these protocols, and often train regulation in both directions (i.e. increase of slow cortical negativity and positivity). Although the beneficial effects on clinical

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ADHD symptoms are beyond doubt, the mechanisms leading to these improvements remain unclear. Several authors (Bakhshayesh et al. 2011; Drechsler 2011; Lansbergen et al. 2011; Loo and Barkley 2005; Monastra et al. 2002) have argued that NF training involves considerable nonspecific effects and constitutes a sophisticated form of cognitive-behavioral training, whereby children learn to focus on attentional processes, improve feelings of self-efficacy, and are rewarded for sitting still. In addition, EEG frequency or polarity changes, which appear due to active cortical regulation, may instead be induced by respiration, eye movements or other muscle contraction. The specific contribution of cortical regulation to the physiological and clinical effects of NF must therefore be established using proper controls. "Sham" or "mock" NF utilizes the same setting and interface to fed back nonspecific or non-contingent signals which allows for (double-) blind placebo controlled designs, and probably presents the most powerful control condition in order to investigate the specificity of NF training effects. As "regular" and "sham" NF training are equivalent in all other aspects of setting, differences in clinical outcomes can be attributed to the specific effects of learned cortical regulation. Besides serious methodological difficulties associated with this approach (e.g. see Lansbergen et al. 2011), researchers may be reluctant to provide sham feedback to children with ADHD over several months for study purposes due to ethical reasons. Another BF method with "correct" feedback signals may therefore represent the second best choice. From a theoretical and practical perspective, electromyographic biofeedback (EMG-BF) aiming at motor control rather than the regulation of cortical activity seems to be a suitable control method for investigating the specificity of NF and the effects of learned cortical control on behavior. The same training software programs may be used in very similar therapeutic settings. Type, timing and amount of feedback can be closely matched, and the same amount of training time is spent with the therapist. Characteristic nonspecific BF-effects such as improved feeling of self-efficacy, improved self-awareness, and learning of behavioral contingencies should potentially result from both types of training.

To date, only one NF training study has used EMG-BF as a control condition with ADHD patients, using a simple tonic and unidirectional NF protocol. Bakhshayesh et al. (2011) compared NF training of the theta-beta frequency bands ratio with EMG-BF training of the frontal muscles. In their EMG-BF control condition, children were rewarded when muscle activity fell below baseline. Parents reported a significantly stronger reduction of inattention following NF than EMG-BF, although overall ADHD symptoms improved after both training types. However, there are several limitations of this simple type of EMG-BF. First, this unidirectional tonic EMG-BF can not control for the more complex NF protocols with bidirectional tonic and phasic regulation. Second, a simple BF of muscle relaxation may be easier and induce more rapid learning than complex NF training protocols in which learned activation and deactivation is contrasted, and different methods like SCP and frequency band training are combined (e.g. Gevensleben et al. 2009).

Our aim was therefore to develop an EMG-BF training protocol to match a complex NF training as in Liechti et al. (2012) (similar to those used by Gevensleben et al. 2009; Wangler et al. 2011) as closely as possible.

Method Development

Reference NF Training Method

The reference NF contain protocols of the training of frequency bands and of SCPs (Table 1). In the "tonic" training protocol with training of theta-beta frequency bands, a decreased theta-beta ratio (activated state) or an increased theta-beta ratio (deactivated state) has to be maintained over several minutes. The time during which the trainee successfully maintains his cortical activation within the desired range is rewarded, indicated as continuous count.

In the SCP or "phasic" training protocol, shifts of central electrical brain potential on the scalp in the negative (=activation) or positive (=deactivation) direction are fed back to the participants during trials lasting for approximately 10 s. Typically, each SCP trial consists of a short baseline phase, after which instruction regarding the direction of change is given. This is then followed by a feedback phase of a few seconds, during which the potential shift is supposed to occur. The activation is usually continuously fed back and a successful shift, i.e. when the child activates or deactivates above threshold, is rewarded by a bonus point.

The NF training software "SAM" used in this study was developed for children with ADHD by Heinrich (Gevensleben et al. 2009) and is constructed as a computer adventure game.

EMG-BF Training Procedures

For EMG muscle activity detection two electrodes were placed on both arms on the muscle *extensor digitorum*, which is especially important for writing and pen grip (Fig. 1). To allow concomitant EEG recording during the EMG-BF training and ensure artifact control, it was necessary to focus on isometric muscle contraction and on small scale movements such as regular circular pen

Table 1 Matched training procedures of EMG-BF and NF

	Tonic condition		Phasic condition	
	Deactivation	Activation	Deactivation	Activation
EMG biofeedback	1. Dominant hand: Decrease of arm muscle tonus below threshold while performing circular drawing movement 2. Other hand: Reduction of arm muscle tonus below threshold while balancing arm on soft ball	1. One hand: Increase of arm muscle activity by pulling the hand-dynamometer (upper limit = 6 × baseline activity) 2. Other hand: Reduction of arm muscle activity while balancing arm on soft ball	One hand: Producing *less* arm muscle activity during feedback phase (4 s) by releasing the hand-dynamometer	One hand: Producing *more* arm muscle activity during feedback phase (4 s) by pulling the hand-dynamometer (upper limit = 6 × tonic baseline activity)
		Left/right hand alternately	Left/right hand alternately	
Duration	2 blocks of 3 min	2 × 2 blocks of 3 min	4 blocks of 30 activation/deactivation randomized trials	
Neurofeedback analogue	Training of frequency bands 1. Increase of theta activity 2. Decrease of beta activity	Training of frequency bands 1. Decrease of theta activity 2. Increase of beta activity	SCP: central positive shifts on the scalp	SCP: central negative shifts on the scalp
Duration	2 blocks of 4 min	2 blocks of 8 min	4 blocks of 40 activation/deactivation randomized trials	

movements. The EMG-BF training exercises thus aimed at improved force control, bimanual coordination, and smooth, automated writing or drawing movements. For this purpose, the following auxiliary material was used: a hand dynamometer (Bremshey BRSFU238 Accell Fitness, Almere, Netherlands), a writing tablet (Intuos 4 Wacom Co., Saitama, Japan), soft balls and hard rubber balls.

Tonic EMG-BF Training

NF frequency training requires the simultaneous regulation of beta and theta band activity into opposite directions using separate feedback bars for each band. This "dual task" was translated into a bimanual motor task with different concurrent demands for the left and the right hand. Bars on the left and right side of the screen for the feedback of theta and beta activity were used here to indicate arm muscle activity of the left and right hand. To parallel the deactivation and activation trials of the NF frequency training, a tonic motor deactivation and a tonic motor activation task were created. The child was instructed to increase or decrease the height of the bars on the left and right side of the screen by controlling arm motor activity of both hands.

In *the tonic motor activation task* (Fig. 1b; Table 1), muscle activity in one arm had to be kept above a certain threshold while pulling a hand dynamometer. An upper limit was set at six times the baseline activity in order to avoid overexertion. At the same time, contralateral arm muscle activity had to be kept below baseline activity. To this end, a starting position with some measurable tonus was required. This minimal tonus was achieved by positioning the arm on two soft balls, while another ball had to be held in the hand without exerting pressure. The participant was instructed to maintain arm muscle activity for 3 min, by lightly pulling the dynamometer while relaxing the muscles of the other arm. A baseline recording of 1 min with the same instructions preceded the task. Compared to its NF analogue, the duration of the blocks was halved and the number of blocks was doubled in order to avoid overexertion.

In the *tonic deactivation task* (Fig. 1c; Table 1), a circular drawing movement was performed by the writing hand for 3 min while ipsilateral arm muscle activity had to be maintained below threshold. Movements were performed in a drawing template fixed on a writing tablet. Thus, no visual control was needed. Movement velocity and precision were recorded. The writing arm was positioned in a sling fixed on the ceiling in order to reduce interference with irrelevant muscle activity. The contralateral arm was balanced on two balls, while another ball had to be held in the hand. Muscle activity of the contralateral arm also had to be maintained below threshold. Time units with muscle activity of both arms below threshold were rewarded by bonus points. The participant was instructed to draw circles by performing slow, steady

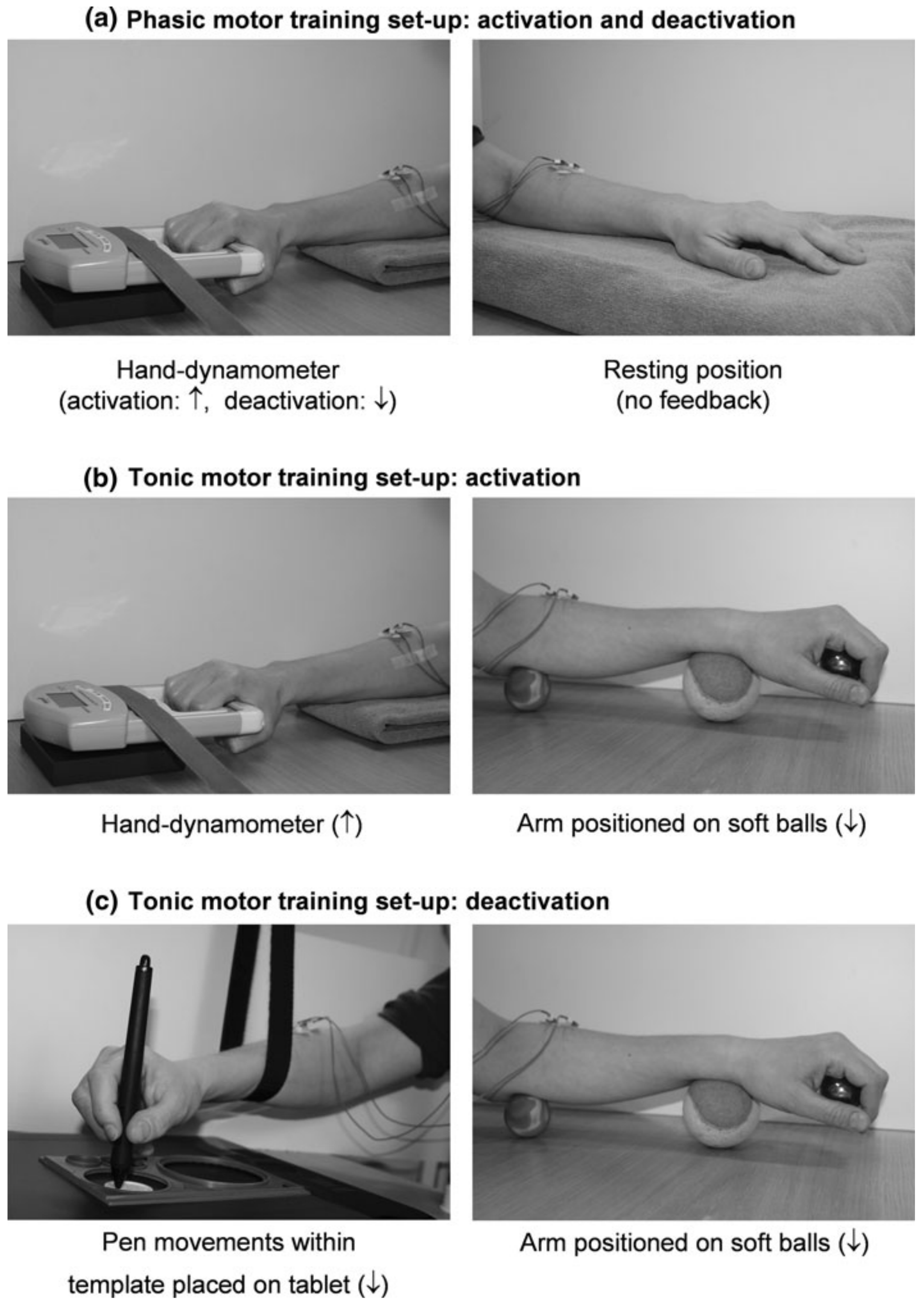

Fig. 1 Training set-ups, devices and tasks of phasic and tonic EMG-BF training. In the phasic training (**a**) and tonic activation condition (**b**), both arms were trained alternately. In the tonic deactivation condition (**c**), only the dominant hand had to deactivate while performing pen movements (↑ increase and ↓ decrease of activation)

pen movements without pressure while keeping muscle activity low. At the same time, the other arm and hand also had to relax. A baseline recording of 1 min with the same instructions preceded the task.

Phasic EMG-BF Training (Fig. 1a; Table 1)

A phasic motor deactivation and a phasic motor activation task were developed in order to match the SCP training. They consisted of short trials in which the child was instructed to find a strategy to move the ball upwards on the screen. Each trial began with a 2 s baseline phase, followed by a 4 s feedback phase. The intertrial interval lasted for 4 s (±1 s). In both task conditions, a dynamometer was pulled by one hand while the other hand rested on the table. In the phasic deactivation task, arm motor activity of the hand pulling the dynamometer had to be decreased, whereas in the phasic activation task, it had to be increased, without exceeding an upper limit. In the phasic motor activation task, the child was instructed to briefly increase muscle activity, but not too much, while keeping the other hand relaxed. In the phasic motor deactivation task, the child was told to progressively relax the grip on the dynamometer, while keeping the other hand relaxed. After a learning phase, activation and deactivation trials were randomized within one training block. To avoid overexertion of the muscles, blocks with dynamometer trials for the left hand and the right hand were alternated.

First Evaluation of the Method: A Case Description of a Child with ADHD Trained by Differential EMG-BF Training

Feasibility of the Method

In order to illustrate the feasibility, course and outcome of our EMG-BF training we present a case report of a 9 year 7 month old boy with ADHD, A.D., who completed this training program. A.D. received EMG-BF training in the context of a clinical study which compared effects of NF training to those of EMG-BF training in children with ADHD. Both training methods were introduced to the children and their parents as experimental BF treatments for ADHD, focusing either on motor or on brain wave activity. The participants agreed to be randomly assigned to one of the two training methods. The presented case was the first child of the EMG-BF training group with complete data and within the originally projected age range of the study and therefore was not selected according to training outcome. The diagnosis was confirmed by the PACS Interview (Parental Account of Children's Symptoms, Taylor et al. 1986) and the Conners' Teacher Rating Scale (CTRS) (Conners et al. 1998b) according to a validated algorithm (see Valko et al. 2010). The child also fulfilled additional study selection criteria, such as IQ $>$ 80, no severe ODD or other severe comorbidity, and no known neurological diseases. He was medication-naive. Parents gave written informed consent and the child assented to take part. The study was approved by the local ethics committee.

A large number of studies on EMG-BF training in ADHD were carried out in the 1980s or earlier most frequently aimed directly at muscle relaxation in order to achieve a better control over hyperactive behavior through the improved ability to reduce movements, to relax muscle tension and to learn to calm down (for reviews, see Arnold 2001; Cobb and Evans 1981; Lee 1991), but with varying and often unsatisfactory methodological standards from a present-day perspective. However, these early studies did neither focus on differential EMG control nor on comorbid motor coordination problems which frequently co-occur in children with ADHD (Fliers et al. 2008; Wilson 2005).

For a first evaluation of the EMG-BF training, we hypothesized that it should be feasible to carry out this control program with an ADHD child and thus to match a complex NF training program in structure and complexity. We expected motor control to improve continuously through EMG-BF in the course of the training and ADHD cardinal symptoms severity to decrease after the training, due to non-specific BF training effects which also contribute to NF. Further, we expected a more pronounced reduction of hyperactivity/impulsivity than of inattention symptoms and improvements on tasks related to fine motor skills and bimanual coordination, as the training is directly aimed at motor control.

Assessment Instruments

Pre- and post-training assessment included behavioral ratings by parents such as the FBB-HKS (Döpfner M. 2000), a German ADHD checklist based on DSM-IV serving as the primary clinical outcome in several NF studies (Gevensleben et al. 2009; Liechti et al. 2012); the Conners' Parents Rating Scale (CPRS), with a test–retest reliability of 0.67 for DSM Inattention and 0.81 for DSM Hyperactivity/Impulsivity (Conners et al. 1998a); the CTRS, with a test–retest reliability of 0.70 for DSM-Inattention and 0.47 for DSM-Hyperactivity/Impulsivity and the following neuropsychological tests:

Tests Without a Primary Motor Component

"Sustained attention", a subtest of the computerized test for attentional performance for children (KITAP, Zimmermann et al. 2002), is a visual continuous performance test of 10 min duration, with a reliability (split-half) of 0.90 for errors and 0.88 for omissions. The D2 test of Attention is a paper-and-pencil cancellation task (Brickenkamp 2002). The outcome measure reported here is the total number of items minus number of errors score (TN-E), with a test–retest reliability of 0.84.

Tests with a Motor Component

The visuomotor precision task is a subtest from the NEPSY (Korkman et al. 1998), designed to assess graphomotor skills. Children have to draw a line through two curved tracks while attempting to remain inside the track lines. The score reflects errors as well as time spent on task with a stability coefficient of 0.71.

In "Flexibility" (KITAP, Zimmermann et al. 2002), the participant has to alternate between two target stimuli. The two stimuli appear simultaneously on the screen, one on the right-hand side and one on the left. The child responds using two buttons, one for the left and the other for the right hand. In the first trial, the child is asked to press the button on the side where the first target is located, in the second trial where the second target is located, and so on.

In approximately half of the trials, the target stimuli change the side. In this case, alternation of targets is not associated with the alternation of hands, and cognitive shifts and hand movements need to be coordinated under effortful control. The split-half reliability of the median of response time is 0.93 and of the errors 0.55. All measures are clinically validated tests and have been used previously in studies on ADHD (e.g. Drechsler et al. 2007; Gevensleben et al. 2009; Maziade et al. 2009).

Subjective Well-Being During Motor Tasks

At the end of each lesson, the child was asked to rate how he had felt during the training tasks, separately for deactivation and activation conditions, on a computerized visual analogue scale (18 cm) with the words “bad” and “good” as well as pictures as visual anchors at the ends of the scales.

Training Protocol

The training consisted of 18 sessions held over a period of approximately 12 weeks. It began with an intensive phase of two to three sessions per week, and then continued with one to two training sessions weekly. Each session comprised two lessons. Additional sessions for pre- and post-training assessments were held before and after the training program. The duration of one session was approximately 3 h, due to the complex experimental setting with concomitant 32-channel EEG recording. The two EMG-BF training lessons accounted for approximately 90 min, including a break. In the first two sessions, the four training conditions were introduced consecutively. At the beginning of the first three sessions, the child performed a progressive muscle relaxation according to Jacobson (Speck 2005). From the second session on, one of the two lessons was scheduled for phasic, and the other for tonic EMG-BF. The order alternated from one session to the next. Within each EMG-BF lesson, both hands (more specifically: arm muscle activity for hand grip) were trained in alternating order from one session to the next. In the tonic training, activation was trained with both hands consecutively, by alternating the order from one session to the next. Deactivation with drawing template was trained only with the dominant hand. In parallel to the NF protocol, transfer trials were introduced after some basic training, i.e. in the 6th session for phasic and in the 9th session for tonic training. In the transfer trials, participants received delayed or no feedback while EMG and EEG were being recorded.

Signal Recording and Processing

To parallel the NF protocol (Liechti et al. 2012), electrophysiological signals were also recorded during the training using 32 active electrodes (AE1, Easy Cap, FMS, Munich), EEG recording reference Fz retrieved by average reference computation, ground at FC6, two EOG (electrooculogram) and one ECG (electrocardiogram) channels. For the EMG-BF training, six electrodes were used for the bipolar recording of EMG signals placed on the *musculus digitorum* of both arms and the *musculus trapezius* of the right shoulder according to the locations and orientations recommended by SENIAM (Hermens et al. 1999) (instead of being used for EEG—Afz, CPz, POz, Iz, FC1, FC2- in the NF protocol). All data were recorded at a rate of 500 Hz using a BrainAmp amplifier (Brain Products, Munich, Germany) with a bandpass filter set at 0.016–250 Hz. In both protocols, a forward filter (Butterworth 2nd order) was used for signal processing, set at 0.1–30 Hz for EEG/ECG and 0.1–100 Hz for EMG signals. The bipolar EMG feedback signal was additionally filtered (55–95 Hz) using Butterworth bandpass filters (48 DB/octave) and rectified for the phasic training. An online eye-artefact correction excluded artefactual ICA components calculated from a resting EEG at the beginning of each training session. Artifacts and muscle tonus above defined thresholds were fed back to the children as a sad face. After initial individual adaptation, artifact thresholds were typically kept constant through the course of training. For offline analysis, the same procedures were used, with the exception of zero phase filters, which were used to avoid unnecessary distortions potentially caused by forward filters.

Analyses of Motor Learning Across Training Sessions

For the analysis of improved motor regulation, the following indices were calculated for all animations with contingent feedback from sessions 2–18 (Table 2).

Tonic EMG-BF

For the tonic EMG-BF, the relative time spent in the desired state of regulation was calculated for each lesson, separately for the activation and deactivation conditions (*time score activation*, *time score deactivation*). These two time scores were defined as the percentage of the training time spent within the desired activation range relative to the total training time free of artifacts. As the threshold for successful regulation was set at each training lesson according to baseline, improved regulation could be expressed by increased time scores as well as by changes in absolute baseline. Therefore, the absolute baseline muscle activity was also included in the analysis. Baseline measures were analyzed separately for the resting arm positioned on soft balls (*baseline resting arm*) and the arm performing the motor activity (*baseline motor arm*). In the tonic deactivation condition, in which decrease of muscle

Table 2 Slope of EMG-BF training parameters by lesson number, indicating changes during the course of the training

		Slope by lesson number
Tonic condition		
Time score (%)	Activation	0.800
	Deactivation	1.240*
Baseline resting arm (μV)	Activation	0.006
	Deactivation	0.174°
Baseline motor arm (μV)	Activation	−0.335**
	Deactivation	−0.023
Tablet (deactivation only)	Speed (r/s)	−0.002
	Imprecision (doc)	−3.519*
Phasic condition		
Time score (%)	Activation	0.185
	Deactivation	1.725***
	Total	0.965***
Muscle activity change from baseline (μV)	Activation	−0.124
	Deactivation	−0.565*
Differentiation (activation–deactivation) (μV)	Total	0.441*

r/s = revolutions per second; doc = degree of coverage

° $0.1 > p > .05$, * $p < .05$, ** $p < .01$, *** $p < .001$

activity should be achieved while performing a circular pen movement on a tablet, *speed* [*revolutions per second* (*r/s*)] and *imprecision* (*degree of coverage*) of movement were both recorded and analyzed with a custom-written program in LabVIEW (National Instruments, Austin, TX, U.S.A.) and in MATLAB (Math-Works, Inc., Natick, MA. Version 2008b), respectively.

Phasic EMG-BF

In analogy to the SCP training, the mean amplitudes of change in muscle activity were calculated for activation and deactivation trials separately (*amplitude deactivation; amplitude activation*). Likewise, in parallel to the SCP training "differentiation", the absolute value of the mean difference between the amplitudes during activation and deactivation trials was calculated for each phasic training lesson (*difference between amplitudes*). The percentage of time spent in the desired range of regulation was calculated for activation and deactivation separately (*time score activation; time score deactivation*). In the phasic training protocol, activation and deactivation trials were presented at random and trained within the same block. As activation and deactivation both depend on baseline activity, *a total time score,* the percentage of total time spent within the desired state of muscle activity was also calculated (Table 2). In addition, the mean EMG trajectories were calculated for phasic deactivation and activation trials of each block across all training blocks and lessons for the right and left arm separately (Fig. 3).

Changes Over Time

To show training effects on muscle regulation over time, linear regressions of EMG-BF scores over lessons were calculated. The slopes representing changes over the course of the training are represented in the results section (Fig. 2). All the reported single-case statistics only test for linear changes over time, and do not allow for generalization across subjects. p Values are estimated based on the assumption of heteroskedasticity and independence of error terms. Therefore, we also report R^2 values as effect size estimators. Time score analyses provided the main outcome measure for the learning of muscular regulation. As the other training parameters served as exploratory measures, we did not correct for multiple comparisons.

Pre- and post-training changes on behavioral ratings and neuropsychological tests were analyzed descriptively. Pre–post differences are expressed in standard deviations of the corresponding scale. The interpretation of results is based on the clinical relevance of pre–post differences. In many neuropsychological tests T-scores below 40 (percentiles (PR) <16) and for scaled scores values below one to two standard deviations under the mean indicate impaired performance (Strauss et al. 2006). In most clinical scales, T-scores above 64 (PR $\geq$ 95) indicate clinical impairment, T-scores between 60 and 64 ($\approx$PR 85–94) subclinical impairment, and T-scores below 60 ($\approx$PR $<$ 85) no impairment. While this matches the common clinical interpretations of the well validated scales, we caution again that our single case results do not allow for generalization.

Results and First Evaluation

Improvements in Learned Motor Regulation

Learning of motor regulation over the course of the training is presented in Table 2 and Fig. 2. A.D. showed improved motor control during tonic feedback in the deactivation condition, with circular pen movements becoming more precise. In the activation condition, baseline activity of the hand pulling the dynamometer decreased over time.

In the phasic protocol, the child increased time scores in the deactivation but not in the activation condition over time. The amplitude of the deactivation condition decrease and the difference between activation and deactivation amplitudes increased over time. As indicated in Fig. 2, the

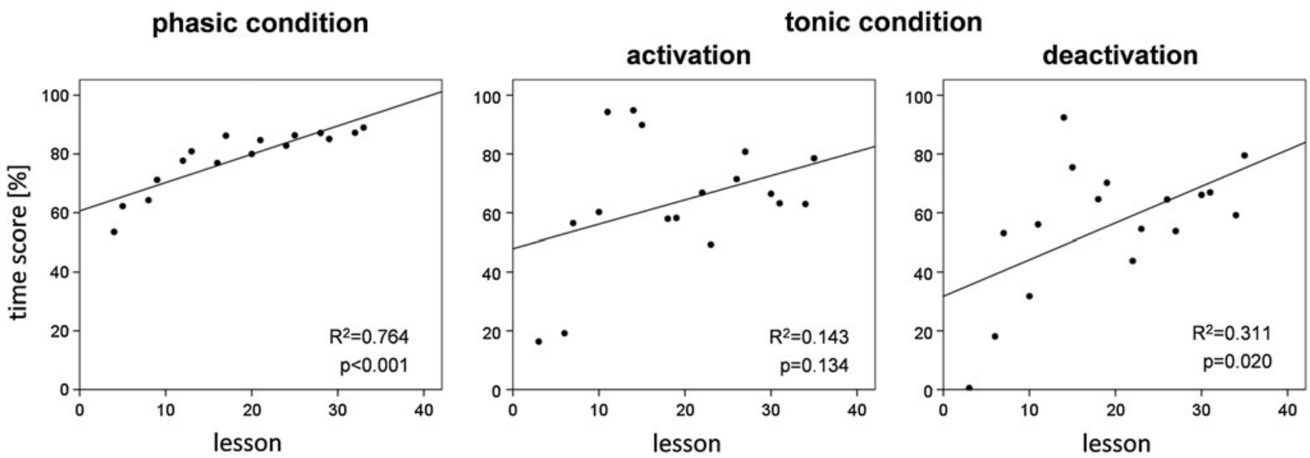

Fig. 2 Course of motor control in phasic and tonic training conditions from sessions 2–18. Time scores relate to the percentage of time spent within the desired range of activity (for corresponding slopes, see Table 2)

total time score started at about 60 % and increased progressively until it reached 90 % at the end of the training.

As illustrated in Fig. 3, deactivation and activation during phasic motor training clearly differed physiologically. Figure 3 also shows that A.D. tended to already increase muscle activity during baseline.

Changes on Behavioral Scales

For parents' ratings on the ADHD checklist FBB-HKS showed a reduction in ADHD symptoms of 26 % (Table 3). On the Conners' scales, parents' ratings were in the normal range after training for both hyperactivity/impulsivity and inattention, which indicates substantial clinical improvement (Table 3). In contrast, teacher ratings remained within the clinical range.

Changes in Neuropsychological Test Performance

In three out of five neuropsychological tests (visuomotor precision, D2, Sustained attention omissions) A.D. showed clinically impaired performances at the beginning. He obtained results within the normal range on all tests after training.

Subjective Well-Being During Motor Regulation Tasks and Clinical Observation

Ratings of well-being during tonic activation and deactivation were in the positive range on average (mean deactivation rating = 32 (±23) and mean activation rating = 17 (±19) on a scale from −100 (=very bad) to plus 100 (=very good)). In the phasic training, ratings of subjective well-being were also positive on average, with a mean deactivation rating = 16 (±34) and a mean activation rating = 42 (±28). According to clinical observation, compliance and motivation was good throughout the training.

Discussion

The goal of the present study was to develop an EMG-BF program that parallels complex NF training, comprising

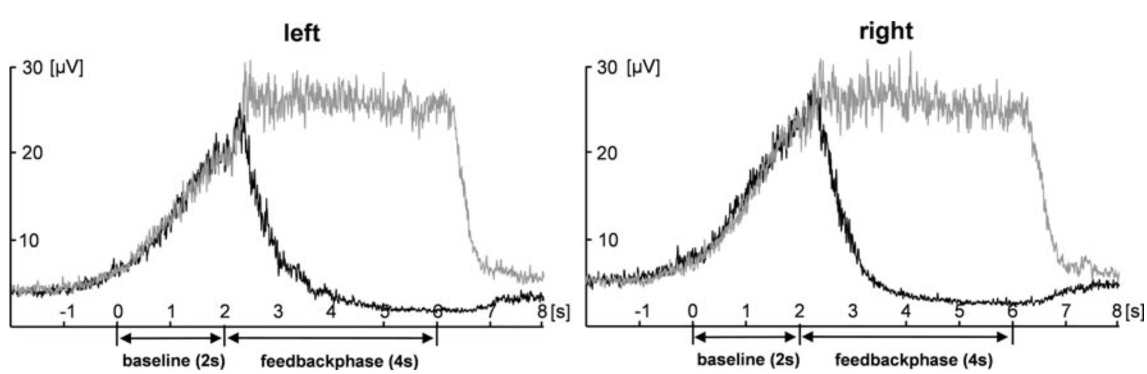

Fig. 3 Means of rectified EMG activity trajectories for the *right* and *left* hand during activation (*gray*) and deactivation (*black*) of all phasic trials (including transfer) from sessions 2–18

Table 3 Pre- and post-results and pre-/post-differences of behavioral ratings by parents and teacher and neuropsychological tests

	Pre	Post	Diff
Behavioral scales			
FBB-HKS			
Total score (R)	1.35	1.00	−26 %
Conners parents			
DSM inattention (T)	63	53	**−1.0 SD**
DSM hyperactivity/impulsivity (T)	68[a]	58	**−1.0 SD**
Conners teacher			
DSM inattention (T)	70[a]	66[a]	−0.4 SD
DSM hyperactivity/impulsivity (T)	83[a]	78[a]	−0.5 SD
Neuropsychological tests			
Visuomotor precision total score (SS)	1[a]	12	**3.6 SD**
Flexibility MD (T)	71	75	0.4 SD
Error (T)	57	>68	**>1.1 SD**
Sustained attention error (T)	58	58	0
Omission (T)	39[a]	47	0.8 SD
D2 TN-E (PR)	16[(a)]	54	**1.1 SD**

Pre pre-training test score, *post* post training test score, *Diff* difference post minus pre transformed in SD. *SD* standard deviation, *T* T-scores, *PR* percentiles, *R* raw scores, *SS* scaled scores (mean = 10; SD = 3). *MD* median response time, *SD-RT* standard deviation of response time. Diffs ≥1 SD are indicated in bold. Behavioral scales: Low scores indicate low impairment; negative SD Diffs indicate improvement. Neuropsychological tests: low scores indicate low performance; positive SD Diffs indicate improvement. Clinical impairments or impaired performances are indicated with [a], borderline impairment with [(a)]

both training of the frequency bands and training of SCPs. We created phasic and tonic EMG-BF training tasks that closely matched the NF training conditions and allowed us to use NF software and matched training protocols.

As indicated by the total time score and illustrated by Fig. 2, A.D. showed increased motor control in the phasic total condition across sessions whereas in the tonic conditions, learning was less consistent. In the tonic activation condition, learning effects were probably masked by the fact that baseline activity of the hand pulling the dynamometer decreased over time. The reduction of the baseline lowered also the upper threshold, decreasing the range of regulation which consequently made regulation probably more difficult. In the tonic deactivation condition, the child had also to improve pen movement precision, what he successfully did, but possibly this additional challenge reduced improvements in the fed back regulation of muscle activity. However, in the main outcome measure for the training success (percentage of time spent in the desired state), the child showed a tendency for improvement over time which indicates that our motor control program is feasible with the different protocol conditions. In addition, positive ratings of well-being indicated that holding or changing muscle activity over several minutes was not associated with unpleasant or painful feelings. The course of the achieved motor regulation across the training (Fig. 2) demonstrates that taken together, A.D. continuously increased his performance over the training sessions. The fact that no ceiling seemed to be reached early on indicates that the method is sufficiently challenging to match a corresponding NF training protocol.

Our first analyses of the EMG data also identified a strategy used by A.D. during EMG-BF phasic training: He tended to increase muscle activity already during the short baseline phase. Thus, during activation trials he could not increase activation any further when the feedback phase began, but during deactivation trials he started from a high activation level and therefore could reduce muscle activity more easily. Consequently, A.D. showed increased time scores in the deactivation but not in the activation condition. This strategy is also reflected by the large decrease of amplitudes in deactivation over time. As activation and deactivation trials appeared randomized on the screen, this strategy had a chance to be effective in half of the trials.

Besides its valuable contribution as NF control training, our EMG-BF training proved to be a clinically effective treatment of some ADHD behaviors in this single case. A.D. demonstrated substantial clinical improvement of ADHD symptoms according to parents' ratings (26 % symptom score reduction on FBB-HKS, which meets the criterion for responders by Gevensleben et al. (2009) of 25 % symptom reduction), and CPRS scores fell below the clinical cut-off after training. Teacher ratings did not indicate comparable improvements. Discrepancies between parents' and teacher ratings concerning the magnitude of change are a common finding in NF studies (see Sonuga-Barke et al. 2013), with teachers usually reporting smaller improvements, if any.

In contrast to our hypothesis, we did not find a differential effect of EMG-BF on hyperactivity/impulsivity compared to inattention symptoms. One possible explanation for this is that unlike previous EMG-BF with ADHD, this EMG-BF was not aimed at motor relaxation, but rather at fine motor skills, placing much higher demands on focused and sustained attention and on executive control. The attentional improvements may indicate that EMG-BF training targeting motor skills to a certain degree also partly constitutes an attention training, which is a "nonspecific" aspect of any demanding BF training. Besides that, there should still be room for specific effects expected for NF training, which hopefully in future studies can be separated from nonspecific effects by using our EMG-BF as a suitable control condition. Likewise, positive trends in neuropsychological performances were not confined to tests with motor components, although practice effects have to be taken into account. Neuropsychological performances were clinically impaired in three out of five tests before and within the normal range after training. Closer inspection of the visuomotor precision task showed that the improvement was mostly due to an increase in speed, therefore the result was obviously in part related to a change of strategy and to familiarity with the test rather than to an improvement of motor precision. Nevertheless, the two neuropsychological tests with motor component showed the most sizable improvements, which probably may be assigned to a specific effect of the EMG-BF training.

The presented results are based on a single subject allowing only a restricted interpretation. For this reason group analyses are needed for further evaluation of the program, particularly with regard to its potential as a treatment for motor coordination deficits.

Conclusion

A differential EMG-BF training procedure could be successfully designed and adapted to closely match the complex training protocols currently used for NF training in clinical practice and research, and effectively tested for feasibility on a child with ADHD.

In addition, it was possible to show that differential motor skill learning resulted from this EMG-BF training in a child with ADHD. Future studies will have to examine its possible value as a specific intervention for children with ADHD and comorbid motor skill problems.

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